

# Search for the Standard Model Higgs Boson in the $p\bar{p} \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$ channel

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We report a search for the standard model (SM) Higgs boson based on data collected by the DØ experiment at the Fermilab Tevatron Collider, corresponding to an integrated luminosity of 260 pb<sup>-1</sup>. We study events with missing transverse energy and two acoplanar *b*-jets, which provide

sensitivity to the  $ZH$  production cross section in the  $\nu\bar{\nu}b\bar{b}$  channel and to  $WH$  production, when the lepton from the  $W \rightarrow \ell\nu$  decay is undetected. The data are consistent with the SM background expectation, and we set 95% C.L. upper limits on  $\sigma(p\bar{p} \rightarrow ZH/WH) \times B(H \rightarrow b\bar{b})$  from 3.4/8.3 to 2.5/6.3 pb, for Higgs masses between 105 and 135 GeV.

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In the standard model (SM) the Higgs boson ( $H$ ) is responsible for electroweak symmetry breaking and has not yet been observed. The experiments at the CERN  $e^+e^-$  Collider (LEP) provide lower limits on its mass,  $m_H > 114.4$  GeV, while electroweak global fits favor a light Higgs boson,  $m_H < 207$  GeV at 95% C.L. [1]. If it exists, the Higgs boson could be observed at the Fermilab Tevatron Collider (center of mass energy  $\sqrt{s}=1.96$  TeV) by combining different analysis channels from both the DØ and CDF experiments [2, 3].

We present a search for a SM Higgs boson with  $m_H$  between 105 and 135 GeV, in the final state with missing transverse energy ( $\cancel{E}_T$ ) and two or three jets, in which one or two jets are identified (“tagged”) as  $b$  jets. This final state is sensitive to Higgs bosons produced in the  $p\bar{p} \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$  channel, which is particularly promising because of the expected large  $Z \rightarrow \nu\bar{\nu}$  and  $H \rightarrow b\bar{b}$  branching fractions. The product of cross section ( $\sigma$ ) and branching fraction ( $B$ ) is predicted to be about 0.01 pb for a 115 GeV Higgs boson, which is comparable to that for  $WH \rightarrow \ell\nu b\bar{b}$  [4].

The chosen final state also has sensitivity to  $WH$  production since the charged lepton from  $W$  decay can be undetected or not identified properly ( $\cancel{E}_T$  channel). Searches for  $WH$  production have been performed previously by relying on the identification of the electron or the muon from leptonic  $W$  decay [5, 6].

There are two main sources of background to this final state: i) the “physics” backgrounds  $Z$ +jets,  $W$ +jets, electroweak diboson production ( $WZ$  and  $ZZ$ ), and top quark production with undetected leptons or jets, and ii) a large instrumental background caused by multijet events with mismeasured jet energies that is difficult to simulate. In the  $ZH$  or  $WH$  processes, since the two  $b$  jets are boosted along the Higgs-momentum direction, they are not back-to-back in azimuthal angle ( $\varphi$ ), in contrast to the dominant dijet background. Our search is based on an integrated luminosity of 260 pb<sup>-1</sup> accumulated with a dedicated trigger designed to select events with significant  $\cancel{E}_T$  and with jets that are not back-to-back.

The DØ tracking system, consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet [7], with tracking and vertexing at pseudorapidities  $|\eta| < 3$  and  $|\eta| < 2.5$ , respectively, where  $\eta = -\ln(\tan(\theta/2))$ , and  $\theta$  is the polar angle. A liquid-argon and uranium calorimeter has a central section (CC) covering  $|\eta|$  up to  $\approx 1.1$ , and two end calorimeters (EC)

that extend coverage to  $|\eta| \approx 4.2$  [8]. An outer muon system, at  $|\eta| < 2$ , consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroids, followed by two similar layers after the toroids.

To estimate the number of expected events, the signal ( $ZH, WH$ ),  $t\bar{t}$ , and diboson production is simulated with PYTHIA [9]. For  $W$  and  $Z$  events with two or more jets we use ALPGEN [10], and for single top simulation we use COMPHEP [11]. The samples generated by COMPHEP and ALPGEN are passed through PYTHIA for showering and hadronization. The cross section for the ALPGEN samples are normalized to next-to-leading-order calculations [12]. All the samples are processed through DØ detector simulation based on GEANT [13], and DØ reconstruction software. Trigger efficiencies measured in data are applied to correct the simulated events.

Event selection requires two or three jets reconstructed with the “iterative-midpoint-Run-II” cone algorithm, with  $p_T > 20$  GeV,  $|\eta| < 2.5$  and a cone radius of  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} < 0.5$ . Jets are required to pass quality criteria designed to reject noise and suppress electron- or photon-induced energy depositions, and jet energies are corrected to the particle level using jet energy calibration and resolution factors determined from photon+jet events. Corrections depend on the  $p_T$  and  $\eta$  of the jet and are typically 30%. Jet energy resolution varies from 20% to 10% for  $p_T$  between 40 and 150 GeV.

The primary vertex has to be within  $\pm 35$  cm in the  $z$  direction, and at least two “taggable” jets passing the above requirements must be present in the event to be included in our final sample. A jet is taggable if it contains within its cone at least two tracks satisfying strict quality criteria, one with  $p_T > 1$  GeV, and another with  $p_T > 0.5$  GeV. The average fraction of taggable jets is measured using  $W(\rightarrow \mu\nu)$ +jets data, and is  $(86 \pm 1)\%$  per jet. This fraction, which is a function of  $\eta$  and  $p_T$  of the jet, and of the  $z$  coordinate of the primary vertex, is used to correct the simulated jets.

We then require: i)  $\cancel{E}_T > 50$  GeV, where  $\cancel{E}_T$  is calculated from the position and energy of the calorimeter cells, ii) the azimuthal angle between the two highest  $p_T$  (leading) jets to be less than  $165^\circ$ , and iii) no isolated electrons or muons, in order to suppress multijet background and  $W(\rightarrow e\nu, \mu\nu)$ +jet, and  $Z(\rightarrow ee, \mu\mu)$ +jet events. For the rejection of  $t\bar{t}$  background, we require the scalar sum  $H_T$  of the  $p_T$  of the jets to be less than 240 GeV. To further reduce instrumental background induced by mismeasurement of jet energy, which produces abnormal  $\cancel{E}_T$ , we define  $\min\Delta\varphi(\vec{\cancel{E}}_T, \text{jets})$  as the min-

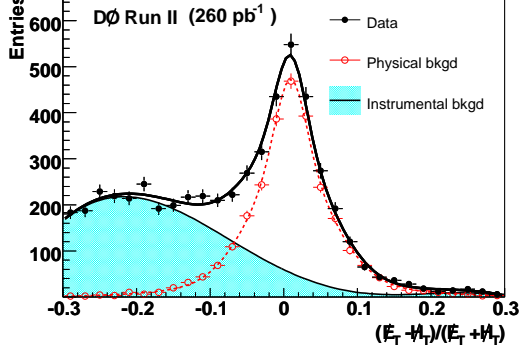


FIG. 1: Asymmetry distribution  $A(\vec{E}_T, \vec{H}_T)$  in the signal region, prior to the imposition of the requirement on  $A(\vec{E}_T, \vec{H}_T)$ . The data is described by the sum of the physics background, modeled by a triple Gaussian, and the instrumental background modeled by a polynomial function.

imum difference in  $\varphi$  between the direction of  $\vec{E}_T$  and any of the jets,  $H_T \equiv |\sum_{i=1}^{n_{jet}} \vec{p}_T|$  as the magnitude of the vector sum of the  $\vec{p}_T$  of the jets,  $\vec{P}_T^{trk} \equiv -\sum_{i=1}^{n_{trk}} \vec{p}_T$  as opposite vector sum of the  $\vec{p}_T$  of all tracks,  $\Delta\varphi(\vec{E}_T, \vec{P}_T^{trk})$  as the difference in  $\varphi$  between the direction of  $\vec{E}_T$  and  $\vec{P}_T^{trk}$ , and  $A(\vec{E}_T, \vec{H}_T) \equiv (E_T - H_T)/(E_T + H_T)$  as the asymmetry between  $\vec{E}_T$  and  $\vec{H}_T$ . The instrumental background is significantly reduced by requiring:  $E_T$  (in GeV)  $> 80 - 40 \times \min \Delta\varphi(\vec{E}_T, \text{jet})$ ,  $|\vec{P}_T^{trk}| > 20$  GeV,  $\Delta\varphi(\vec{E}_T, \vec{P}_T^{trk}) < \frac{\pi}{2}$  and  $-0.1 < A(\vec{E}_T, \vec{H}_T) < 0.2$ . All these requirements define the signal region.

$W(\rightarrow \mu\nu) + \text{jets}$  data are used to confirm that the above variables are well modeled. The instrumental background is then estimated from the data using the signal and a “sideband” region, which is defined by requiring all above selections, except for the requirement  $\Delta\varphi(\vec{E}_T, \vec{P}_T^{trk}) > \frac{\pi}{2}$ . The distribution in the simulated instrumental background generated by PYTHIA gives a qualitative description of this background. This indicates that we are correctly identifying the background source, and we therefore model it using sideband data to avoid uncertainty from the difficult simulation of instrumental background. The physics backgrounds passing the final selection tend to be distributed around  $\Delta\varphi(\vec{E}_T, \vec{P}_T^{trk}) \sim 0$ , while the instrumental background is distributed similarly in the sideband and in the signal region due to mis-measurement of jet energy or of charged tracks.

Figure 1 shows the  $A(\vec{E}_T, \vec{H}_T)$  distribution in the signal region. The amount of physics background in the signal region is estimated using the simulation, and parameterized by a triple Gaussian (TG) function, shown as a dashed line in Fig. 1. The contribution not described by this parameterization is considered to be the instrumental background, and is modeled with a polynomial function tested with a fit to the data in the sideband

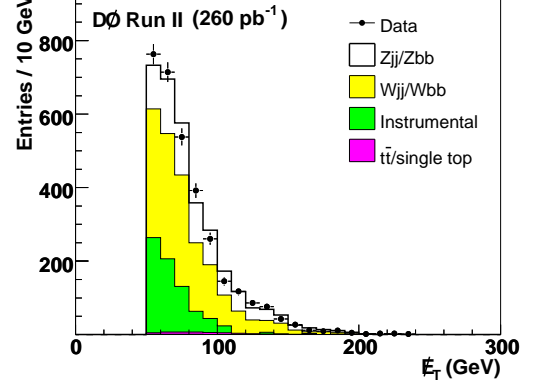


FIG. 2:  $E_T$  distribution after selection except for  $b$ -tagging.

region. The physics background contributes about 15% of the events in the sideband region and is included in the model of instrumental background. The sum of the absolutely normalized TG parameterization and of the polynomial function is then fitted to the data in the signal region, as shown in Fig. 1. (Before  $b$ -tagging, the Higgs signal is negligible.) The instrumental background in the signal region amounts to  $696 \pm 91$  events, while the physics background amounts to  $2520 \pm 330$  events. Since our search requires good modeling of  $E_T$ , we show in Fig. 2 the  $E_T$  distribution after all requirements, excepting  $b$ -tagging. The data are well described by the sum of the simulation of  $Z/W + jj/b\bar{b}$  and the estimated contribution from instrumental background. Top pair and single top pair production represent negligible contributions before requiring  $b$ -tagging.

To select  $b$  jets, we apply a  $b$ -tagging algorithm that uses a jet lifetime probability (JLIP) computed from the tracks associated with the jet. A small probability corresponds to jets having tracks with a large impact parameter that characterize  $b$ -hadron decay. We use two samples for our search: one that requires the two leading jets to pass the  $b$ -tagging condition (double  $b$ -tagged sample, or DT sample); the other requires exactly one jet to pass the  $b$ -tagging condition, and does not accept events from the DT sample (exclusive single  $b$ -tagged sample, or ST sample). The requirements on the lifetime probability are defined by optimizing the sensitivity to Higgs signal. In the DT sample, we require  $\text{JLIP} < 1\%$  for the leading jet and  $< 4\%$  for the second-leading jet. In the ST sample we require a more stringent  $\text{JLIP} < 0.1\%$ . The average  $b$ -tagging efficiency is  $\approx 50\%$  (40%, 30%) for  $\text{JLIP} < 4\%$  (1%, 0.1%). The relative uncertainty on the  $b$ -tagging efficiency is 7% per jet. The mis-tag rate is defined as the fraction of light-quark jets tagged as  $b$  jets, and its average value is approximately the value of the JLIP requirement. For the instrumental background, we estimate the mis-tag rate from data in the sideband

TABLE I: Number of expected signal (for  $m_H = 115$  GeV), background, and observed events (obs.) before  $b$ -tagging, after inclusive (IST), and exclusive (ST) single  $b$ -tagging, and after double  $b$ -tagging (DT). Before  $b$ -tagging, the expected background is by construction equal to the observed events (see text on the background determination). The numbers of events after the  $\pm 1.5$  standard deviation (s.d.) mass window requirement are given in parenthesis. The errors on these numbers are in average 18% (19%) for the ST (DT) sample.

|                                 | $\cancel{E}_T +$<br>2, 3 jets | $\cancel{E}_T +$<br>2, 3 jets<br>IST | $\cancel{E}_T +$<br>2, 3 jets<br>ST | $\cancel{E}_T +$<br>2, 3 jets<br>DT |
|---------------------------------|-------------------------------|--------------------------------------|-------------------------------------|-------------------------------------|
| $ZH$                            | 0.71                          | 0.62                                 | 0.26 (0.20)                         | 0.24 (0.21)                         |
| $WH$                            | 0.54                          | 0.47                                 | 0.20 (0.15)                         | 0.18 (0.15)                         |
| $Zjj$                           | 843                           | 93.3                                 | 7.9 (2.6)                           | 1.4 (0.5)                           |
| $Wjj$                           | 1600                          | 260                                  | 36.1 (13.6)                         | 4.2 (1.5)                           |
| $Zbb$                           | 13.1                          | 11.3                                 | 4.7 (1.6)                           | 4.1 (1.4)                           |
| $Wbb$                           | 12.4                          | 10.5                                 | 4.4 (1.4)                           | 3.6 (1.1)                           |
| $t\bar{t}/t\bar{b}/tqb$         | 42.3                          | 33.6                                 | 15.3 (5.6)                          | 9.0 (3.0)                           |
| $WZ/ZZ$                         | 7.3                           | 3.4                                  | 1.1 (0.71)                          | 0.9 (0.6)                           |
| Instrumental                    | 696                           | 143                                  | 25.0 (8.4)                          | 3.9 (1.3)                           |
| Total expectation $\equiv$ obs. | 555                           | 94.5 (34.0)                          | 27.0 (9.4)                          |                                     |
| Observed events                 | 3210                          | 592                                  | 106 (33)                            | 25 (11)                             |

region, and extrapolate it into the signal region. Table I lists the number of  $ZH$  and  $WH$  signal, background and observed events for each  $b$ -tag requirement, and also for the inclusive sample of events with at least one  $b$ -tagged jet with  $JP < 4\%$  (to verify that the data are also well described by the simulation in another  $b$ -tagging configuration). After the ST requirement, 106 events remain, while  $94.5 \pm 17.0$  events are expected. In the DT sample, we observe 25 events, while  $27.0 \pm 5.1$  are expected, and in the inclusive sample these numbers are 592 and  $555 \pm 70$  events, respectively.

We estimate the systematic uncertainty due to trigger and jet reconstruction efficiency, jet energy calibration, jet resolution,  $b$ -tagging, instrumental-background estimation, physics-background cross sections and parton distribution functions, by varying each source of uncertainty by  $\pm 1$  s.d. and repeating the analysis. The systematic uncertainties are estimated separately for the DT and ST samples. In total, we find a 19% (14%) uncertainty on signal acceptance and 19% (18%) uncertainty on the total background for the DT (ST) analysis. The dominant systematic uncertainties are due to  $b$ -tagging and jet reconstruction and calibration. The uncertainty on the integrated luminosity is 6.5%.

We then search for an excess of events as a function of  $m_H$  by counting events in the dijet mass distribution within a  $\pm 1.5$  s.d. window around the reconstructed Higgs-boson mass peak, e.g.,  $\pm 25.2$  GeV for  $m_H = 115$  GeV. No excess over the SM background is found in the data, as can be seen for the DT dijet mass distribution in Fig. 3, in which the expected  $ZH$  signal for  $m_H = 115$  GeV is also shown. The acceptance for  $ZH$  ( $WH$ ) events

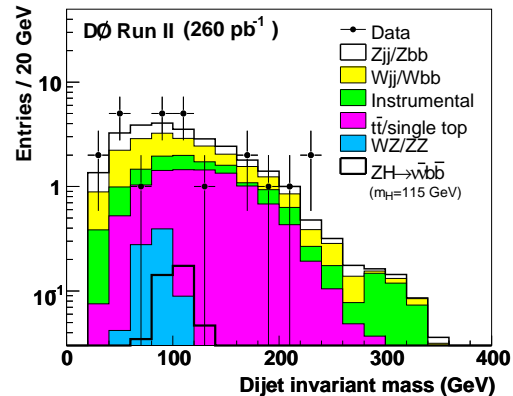


FIG. 3: Dijet invariant mass distribution in the DT sample. The expectation originating from  $ZH$  production with  $m_H = 115$  GeV is also shown.

is 1.04% (0.43%) for  $m_H = 115$  GeV. We thus set 95% C.L. upper limits on  $\sigma(p\bar{p} \rightarrow ZH) \times B(H \rightarrow b\bar{b})$  and  $\sigma(p\bar{p} \rightarrow WH) \times B(H \rightarrow b\bar{b})$ , using a modified frequentist approach, the  $CL_s$  method [14]. In this method, the binned distributions are summed over the log-likelihood ratio test statistic. Systematic uncertainties are incorporated into the signal and background expectations using Gaussian sampling of individual uncertainties. For the limits obtained when combining the likelihoods of the ST and DT analyses, correlations between uncertainties are handled by varying simultaneously all identical sources. Limits are determined by scaling the signal expectations until the probability for the background-only hypothesis falls below 5% (95% C.L.). This translates into a cross-section limit for  $\sigma(p\bar{p} \rightarrow ZH) \times B(H \rightarrow b\bar{b})$  of 3.2 pb and for  $\sigma(p\bar{p} \rightarrow WH) \times B(H \rightarrow b\bar{b})$  of 7.5 pb, assuming  $m_H = 115$  GeV. The limits for four Higgs mass points (105, 115, 125, and 135 GeV) and for ST, DT, and the combined ST+DT results are summarized in Tables II and III. We set 95% C.L. upper limits from 3.4 to 2.5 pb on  $\sigma(p\bar{p} \rightarrow ZH) \times B(H \rightarrow b\bar{b})$  for  $m_H = 105$ –135 GeV (Fig. 4). The CDF collaboration has published combined limits (ST+DT) with Tevatron Run I data, i.e. at  $\sqrt{s} = 1.8$  TeV, of 7.8–7.4 pb for  $m_H = 110$ –130 GeV [15].

In conclusion, we have performed a search for  $ZH$  and  $WH$  associated production in the  $\cancel{E}_T + b$  jets channel using 260  $\text{pb}^{-1}$  of data. We have studied the dijet mass spectrum of the two leading jets with double and exclusive single  $b$ -tagged jets for Higgs boson masses between 105 and 135 GeV. In the absence of signal, we have set upper limits on different Higgs production channels/final states, and have combined them. The combined limits are between 3.4 to 2.5 pb (8.3 to 6.3 pb) on the cross section for  $ZH$  ( $WH$ ) production multiplied by the branching fraction for  $H \rightarrow b\bar{b}$ . These are the first limits in the  $ZH$  channel based on Tevatron Run II data.

TABLE II: Expected/observed 95% C.L. limits on  $\sigma(p\bar{p} \rightarrow ZH) \times B(H \rightarrow b\bar{b})$  in pb, as a function of  $m_H$ .

| Higgs mass (GeV) | 105     | 115     | 125     | 135     |
|------------------|---------|---------|---------|---------|
| ST               | 7.7/8.2 | 6.8/6.8 | 6.0/7.3 | 5.4/7.5 |
| DT               | 3.3/4.2 | 2.8/3.6 | 2.5/2.8 | 2.2/2.2 |
| ST+DT            | 3.1/3.4 | 2.7/3.2 | 2.4/2.9 | 2.1/2.5 |

TABLE III: Expected/observed 95% C.L. limits on  $\sigma(p\bar{p} \rightarrow WH) \times B(H \rightarrow b\bar{b})$  in pb, as a function of  $m_H$ .

| Higgs mass (GeV) | 105       | 115       | 125       | 135       |
|------------------|-----------|-----------|-----------|-----------|
| ST               | 18.5/17.6 | 15.9/16.9 | 14.9/18.9 | 12.4/18.5 |
| DT               | 8.0/9.6   | 6.6/8.1   | 6.3/7.1   | 5.3/5.3   |
| ST+DT            | 7.6/8.3   | 6.3/7.5   | 6.0/7.4   | 5.0/6.3   |

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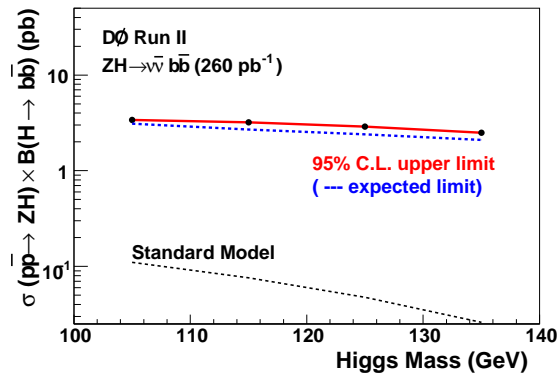


FIG. 4: 95% C.L. upper limit on  $\sigma(p\bar{p} \rightarrow ZH) \times B(H \rightarrow b\bar{b})$  (and corresponding expected limit) for  $ZH$  production vs. Higgs mass, as derived from the ST+DT combination.